



Toward Fast, Low-noise, Low-Power CCDs for Lynx & Other High-Energy Missions

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Acknowledgements

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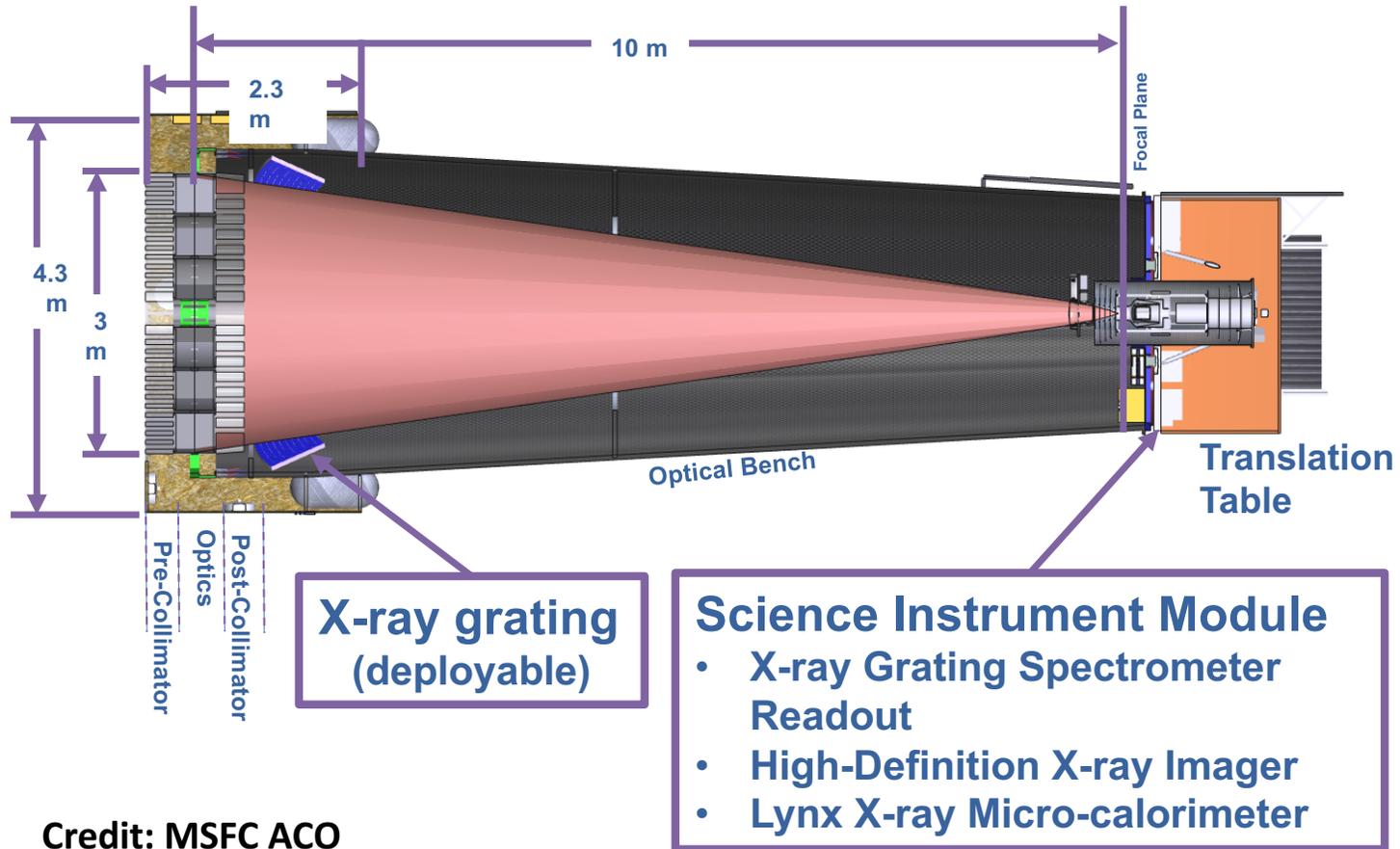
The MIT Lincoln Laboratory Digital CCD effort has been supported by the Department of the Air Force.



Overview

- Why consider CCDs for Lynx?
- Advances in CCD technology at MIT Lincoln Laboratory
- Recent measurements of CCD performance
- Challenges for Lynx detectors
 - Small, tall pixels
 - Radiation tolerance
- Next Steps

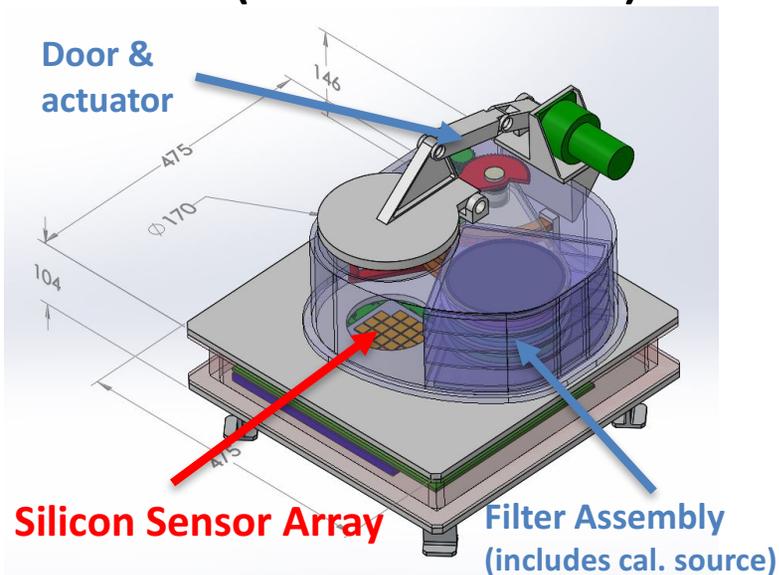
Lynx Configuration



Credit: MSFC ACO

Silicon Imaging Detectors for Lynx

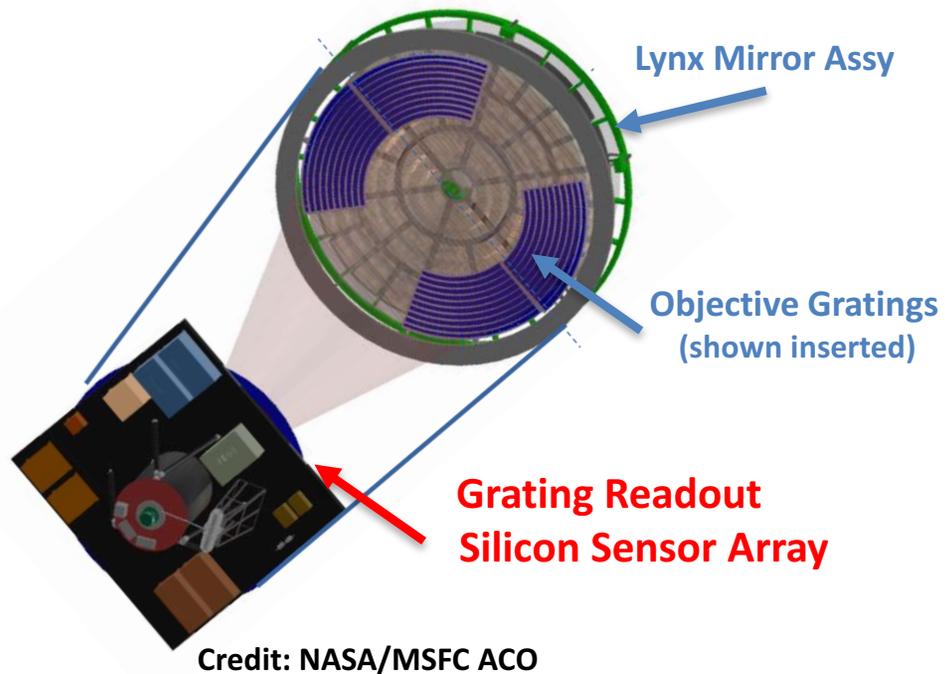
High-Definition X-ray Imager (HDXI) (Abe Falcone's talk)



Credit: NASA/GSFC IDL

Focus of this talk

X-ray Grating Spectrometer (XGS) (Moritz Günther's & Randy McEntaffer's talks)



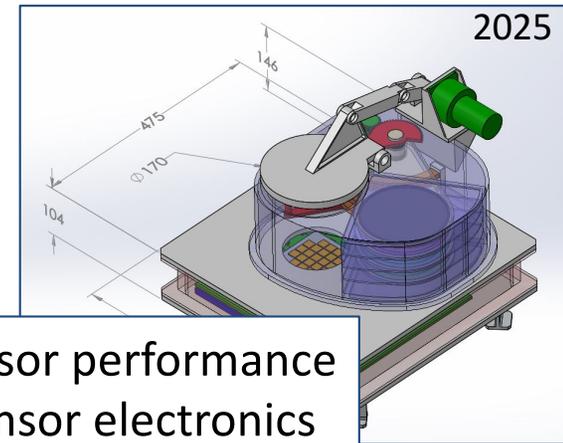
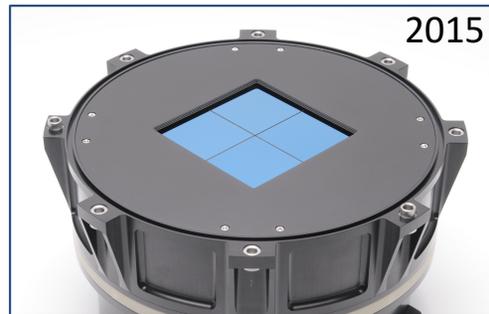
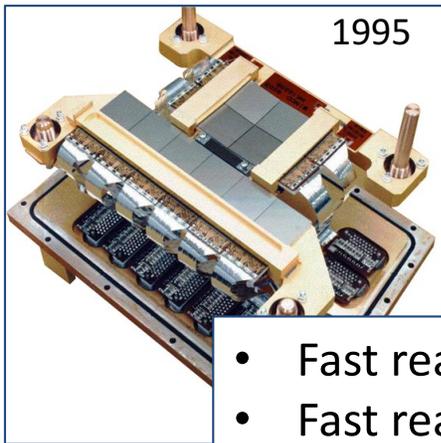
Credit: NASA/MSFC ACO



Lynx HDXI Requirements

Parameter	Requirement	Remarks
<i>Primary Science Requirements:</i>		
Energy Range	0.3 – 10 keV	<i>Low energies critical for prime high-z & low kT science</i>
Field of View	22 x 22 arc-minutes	PSF < 1" HPD over 10' radius field
Spatial Resolution	Pixels size 0.33 arc-seconds	≤ 16 μm (Lynx focal length = 10m)
Spectral Resolution	60 eV FWHM @ 1 keV	
<i>Derived Requirements:</i>		
Read noise	≤ 4 electrons RMS	Driven by low-E detection efficiency requirement
Count rate capability	8000 ct s ⁻¹	Full field
Frame Rate	100 frame s ⁻¹ full field 10 ⁴ windows s ⁻¹ (~7" x 7" window)	

What's so hard about the HDXI focal plane?



- Fast readout + low noise mainly drives sensor performance
- Fast readout + low power mainly drives sensor electronics

Chandra ACIS-I focal plane:

- 2k x 2k, 24 μm pixels
- 45 μm depletion (BI)
- 2-3 e^- read noise
- 0.3 frames s^{-1}
- 40 W; 30 μJ pixel $^{-1}$

TESS focal plane (1 of 4):

- 4k x 4k, 15 μm pixels
- 100 μm depletion (BI)
- < 10* e^- read noise
- 0.6 frames s^{-1}
- < 6W; 0.6 μJ pixel $^{-1}$

Lynx HDXI focal plane:

- 4k x 4k, 16 μm pixels
- 100 μm depletion (BI)
- $\leq 4 e^-$ read noise
- **100 frames s^{-1}**
- **$\lesssim 50$ W; 0.03 μJ pixel $^{-1}$**



Why CCDs for Lynx

CCDs:

- Are well-understood
- Have very low noise & excellent uniformity
- Benefit from continuing development

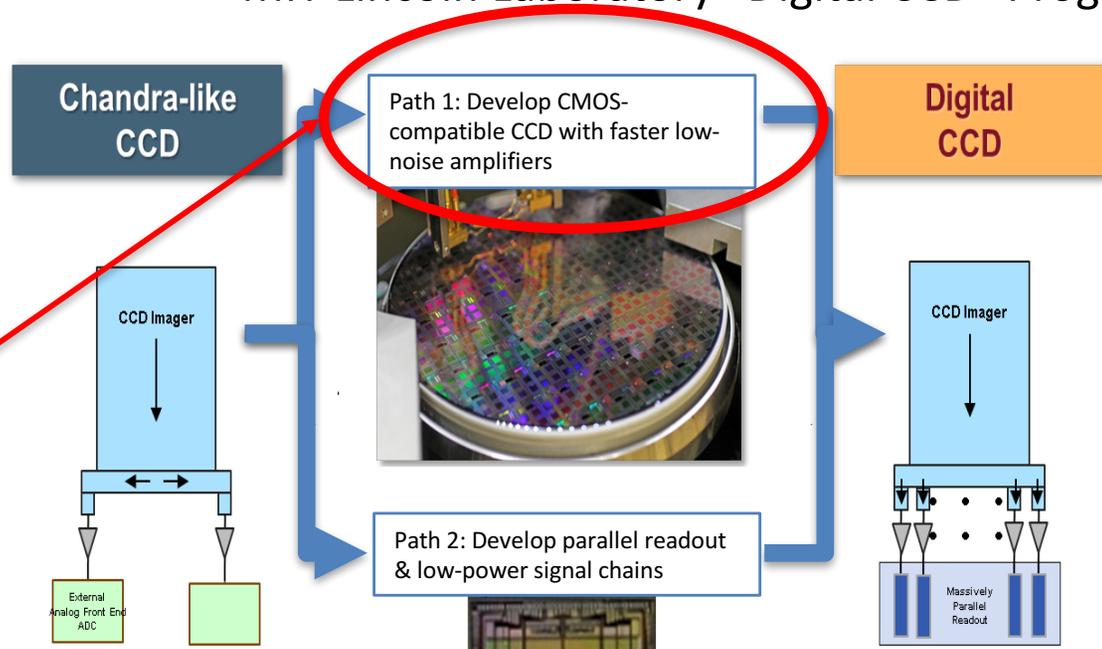
Challenges for conventional CCDs for Lynx:

- Readout speed
- CMOS compatibility & power consumption
- Radiation tolerance

Advancing CCD Technology

MIT Lincoln Laboratory "Digital CCD" Program

This talk



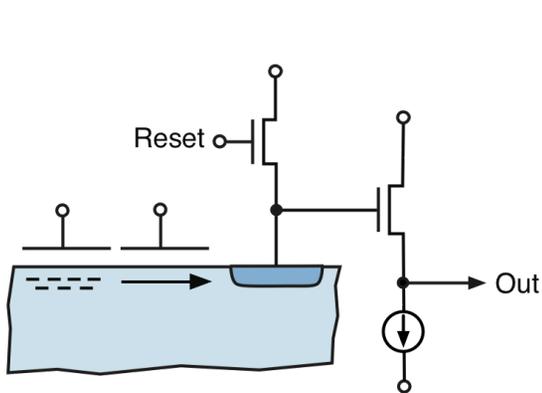
- Simple pixels
- Serial readout
- Low noise at low frame rates
- Large SWaP

- Simple pixels
- Massively parallel readout
- CMOS compatible clock levels for low SWaP
- Low noise at high frame rates
 - High-speed, low-noise, low-power amplifier
 - Integrated video chain

For Lynx:
output rate
→ ~5 MHz

output multiplicity
→ 32-128/chip

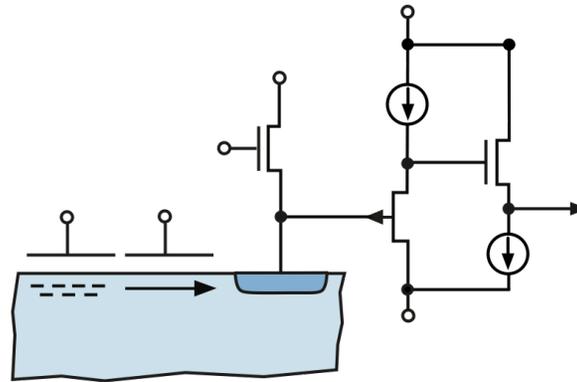
Faster, quieter CCD Amplifiers



nMOSFET

Chandra/Suzaku

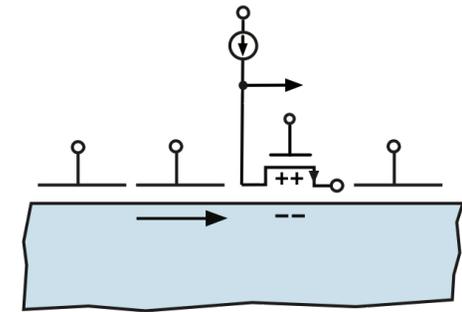
- Low noise
- < 1 MHz



pJFET (with 2nd-stage
nMOSFET)

Current (this talk)

- Low noise
- 1.25 – 5 MHz



SiSeRO pMOS

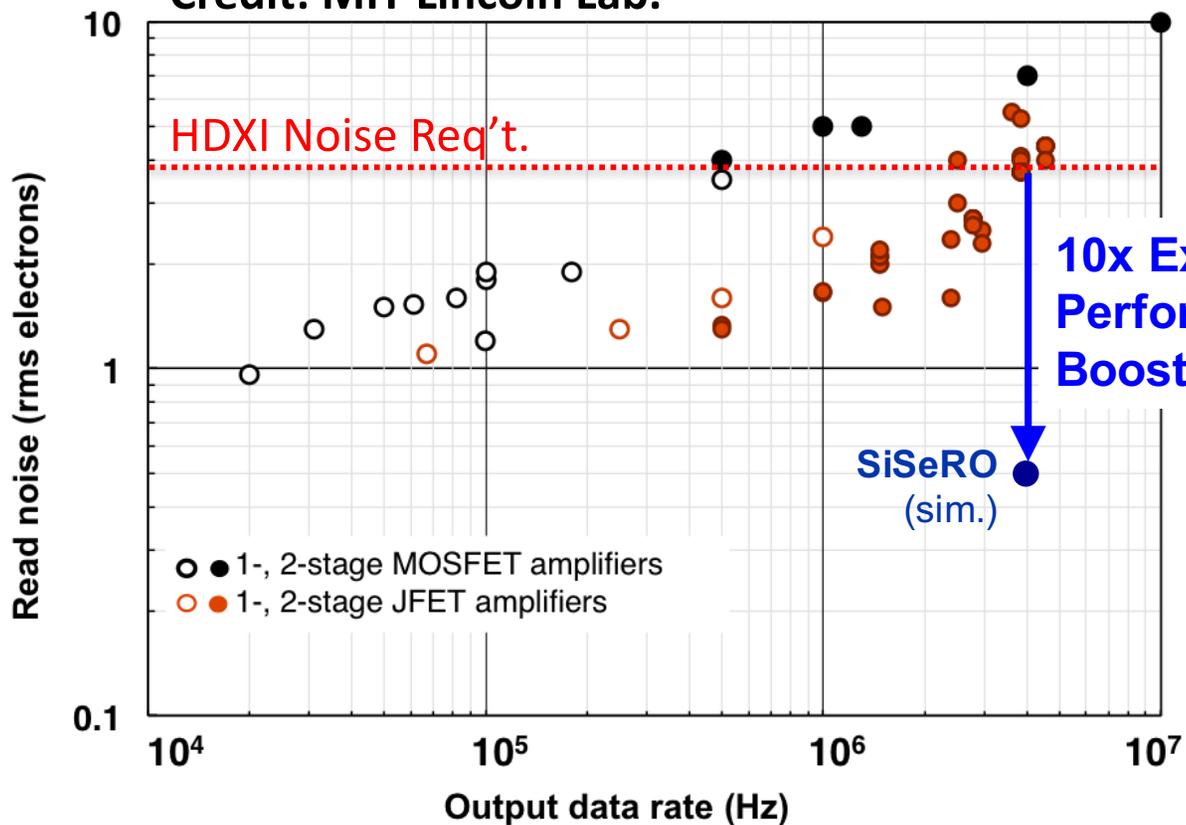
Credit: MIT Lincoln Lab.

In development. Goals:

- Sub-electron noise
- 5 MHz
- Non-destructive read

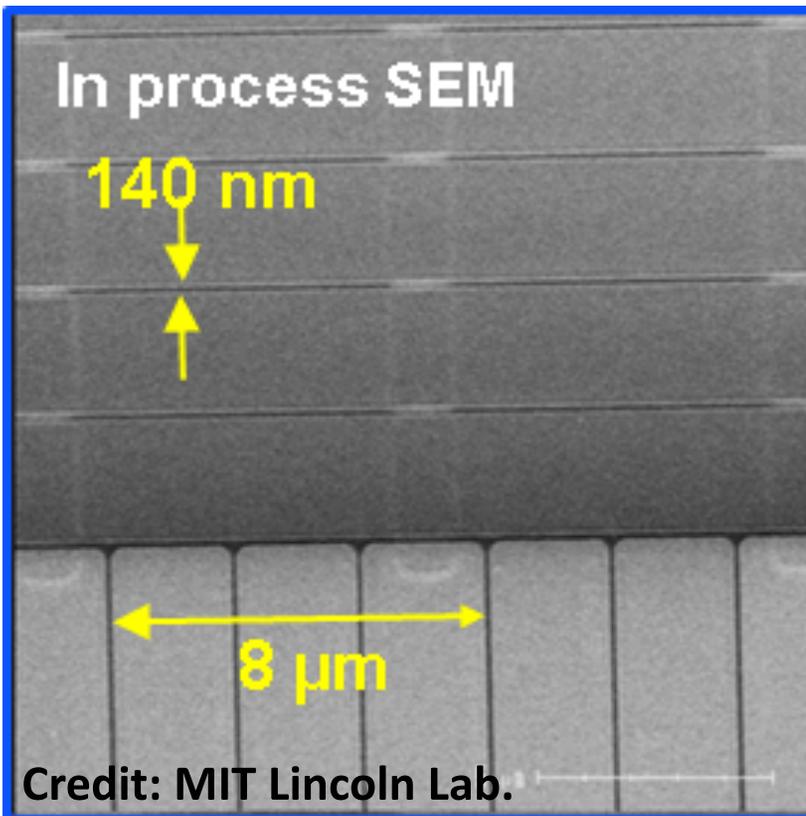
Faster, quieter CCD Amplifiers

Credit: MIT Lincoln Lab.



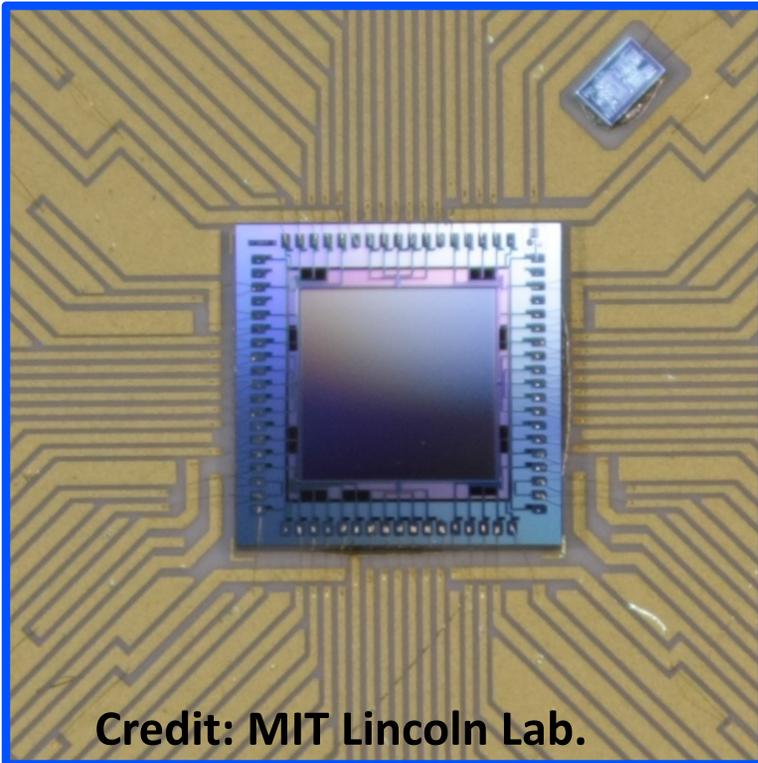
- Chandra/Suzaku
- Current pJFET
- In development SiSeRO

CMOS Compatible Charge Transfer



- Single-level polysilicon process + deep submicron lithography
- Provides efficient charge transfer with CMOS compatible clocks swings ($\pm 1.5 \text{ V}$)
- Reduces power required for clocking ($P \sim CV^2f$) by more than 10x

First generation DCCD Test Device (CCID85)



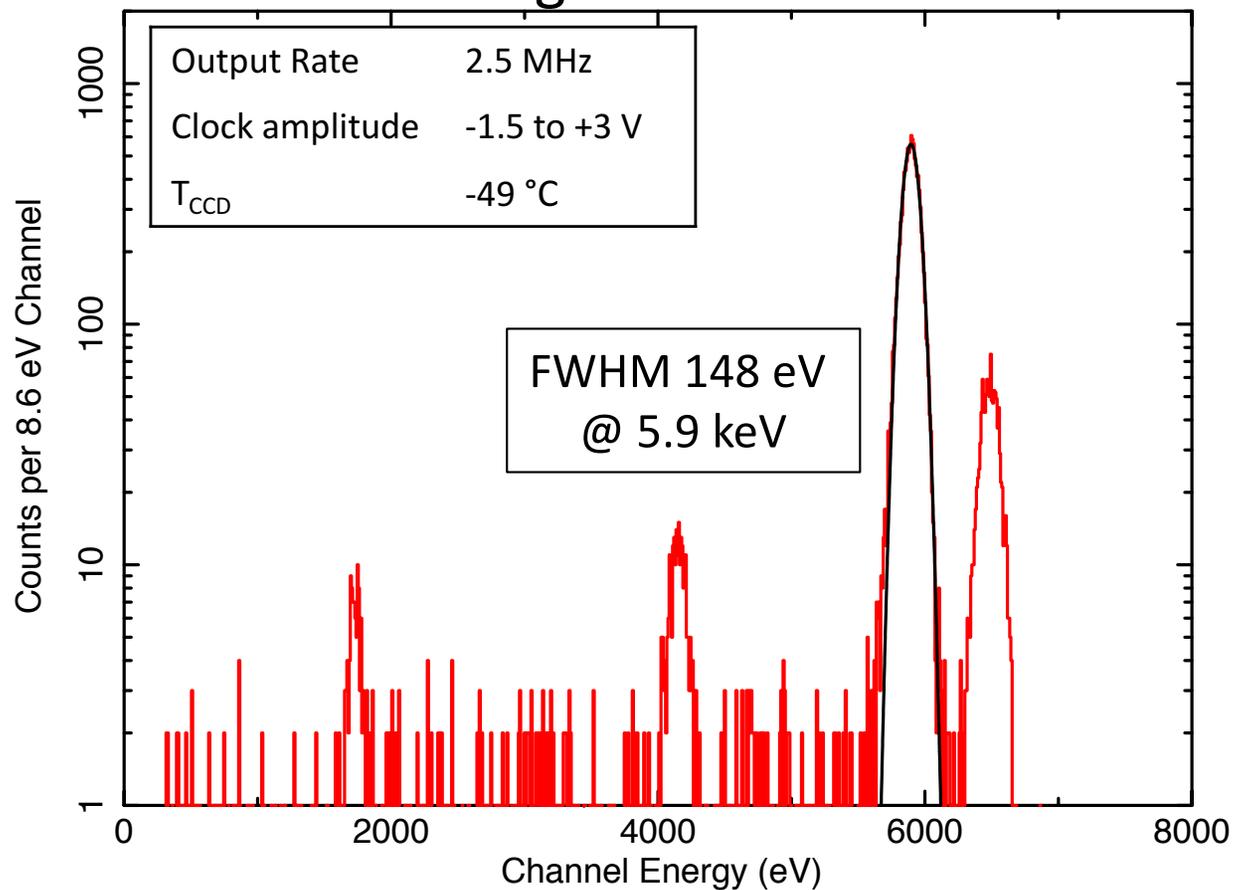
Credit: MIT Lincoln Lab.

- 512 x 512, 8 μm pixels
- pJFET amplifier (1-5 MHz) & (low-speed) SiSeRO
- Single-poly, CMOS-compatible clocks
- Front-illuminated, $\sim 70 \mu\text{m}$ depletion



DCCD test results: X-ray Spectrum

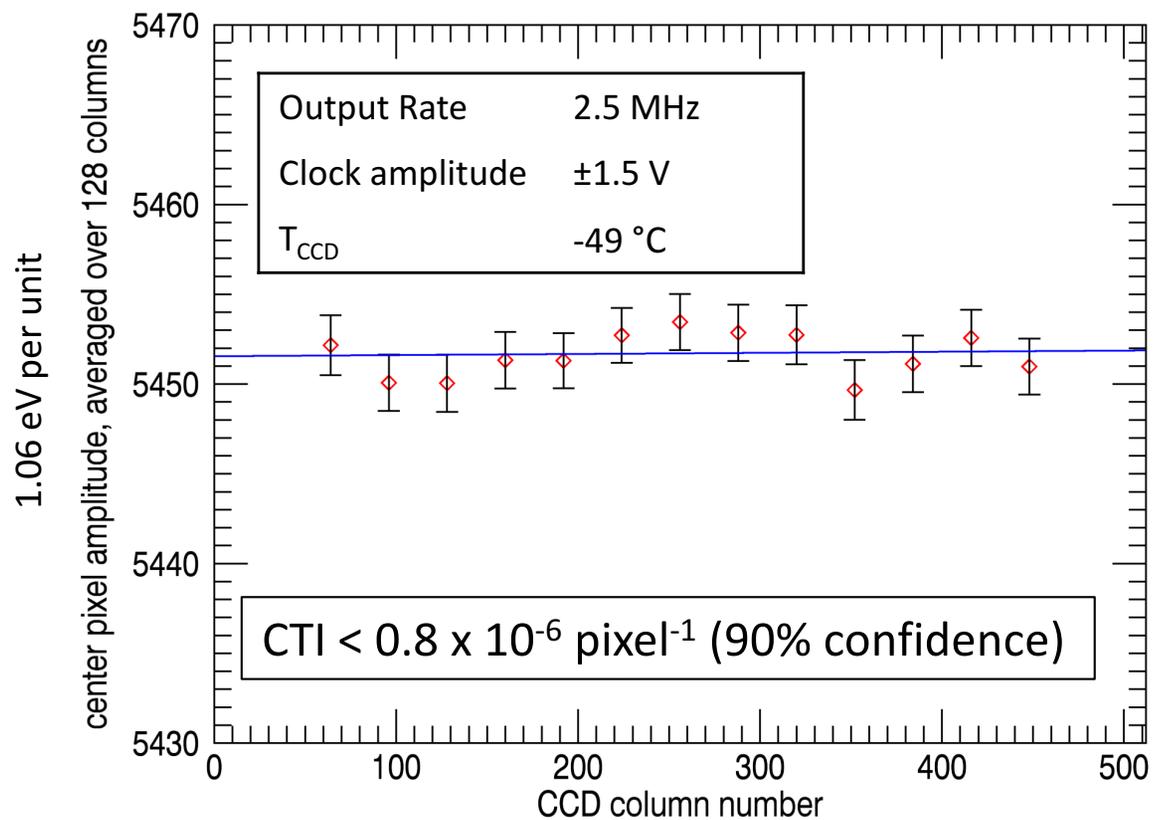
Single-Pixel Events





DCCD test results: Charge Transfer Inefficiency

Output Register



DCCD Test Results

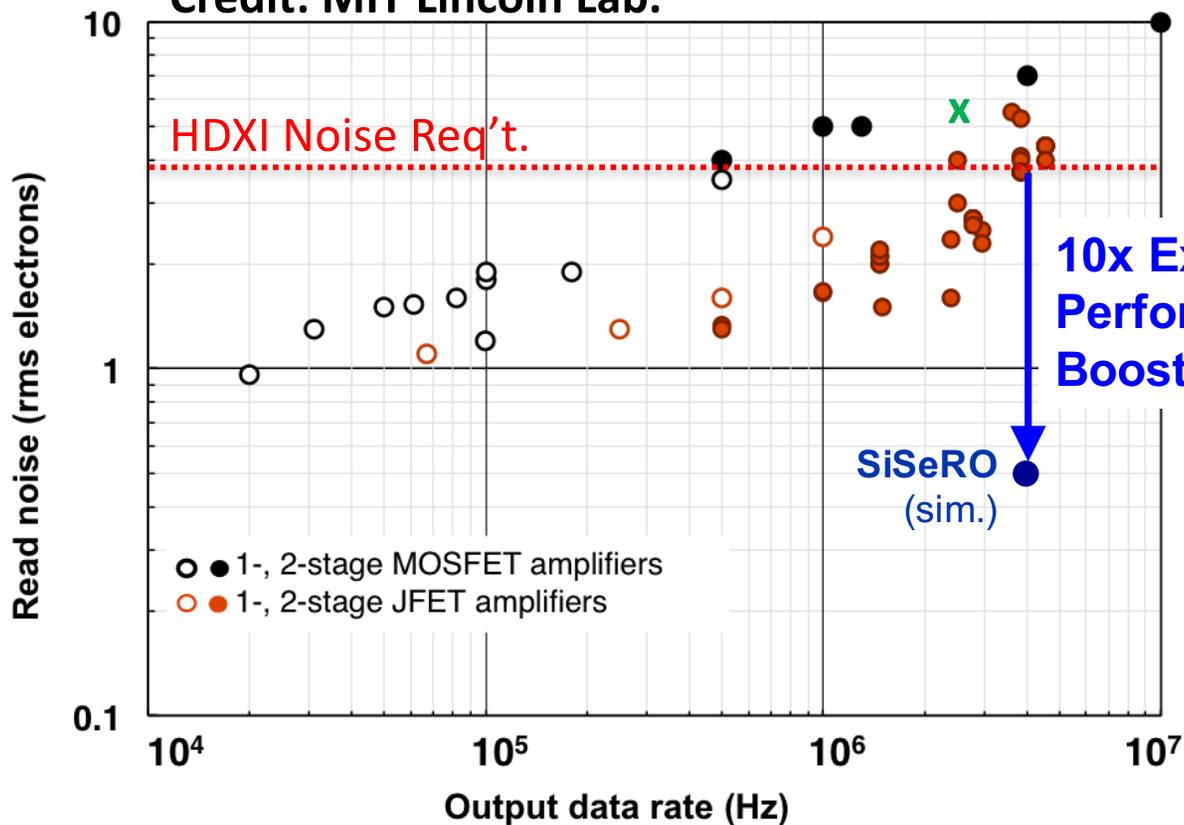
Parameter	Value	Remarks
<i>Operating conditions:</i>		
Pixel rate	1.25 - 5 MHz	
Clock levels (parallel & serial)	-1.5 V to +3 V (typical) -1.5 V to +1.5 V (CTI measurements)	±1.5 V is minimum swing allowed by lab electronics
Detector temperature	-49° C	
<i>Measured performance with pJFET amplifier:</i>		
Responsivity	21 μ V per electron	
System read noise	6.5 - 7.2 electrons RMS @ 2.5 MHz 10 electrons RMS @ 5 MHz	Includes lab electronics noise of 3.3 electrons RMS
Inferred pJFET read noise	5.5 - 6.4 electrons RMS @ 2.5 MHz 9.4 electrons RMS @ 5 MHz	Excluding lab electronics noise
Spectral Resolution	148 - 151 eV FWHM @ 5.9 keV	single-pixel events
Charge Transfer Inefficiency	Parallel: $(3.0 \pm 1.0) \times 10^{-6}$ per transfer Serial: $< 0.8 \times 10^{-6}$ per transfer	@ 5.9 keV; 90% confidence
Dark current	2.0 electrons per pixel per second	@ -49 °C

Read noise:
5.5 – 6.4 e⁻

Noise Comparison

Credit: MIT Lincoln Lab.

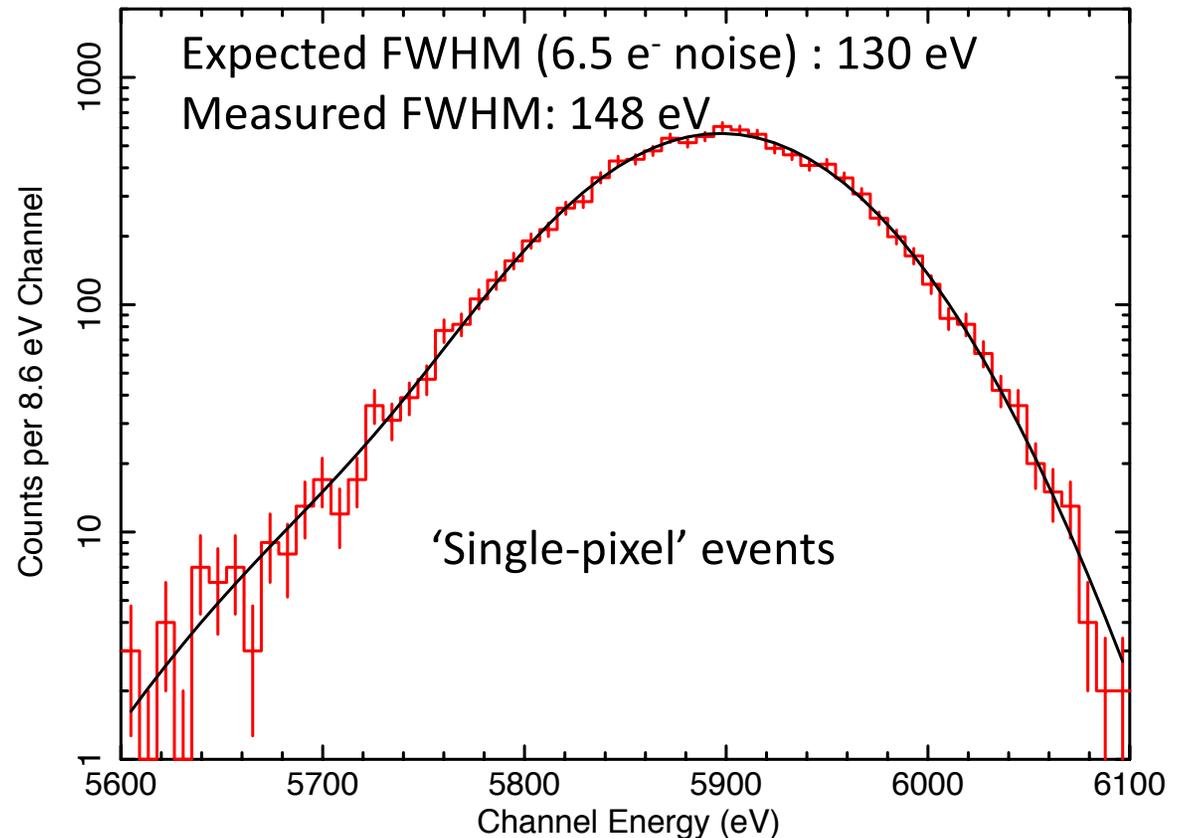
X This work pJFET



- Chandra/Suzaku
- Current pJFET
- In development SiSeRO

Small-But-Tall Pixel Effects

- Similar to HDXI, our test device has relatively small ($8\ \mu\text{m}$) but 'tall' ($70\ \mu\text{m}$) pixels
- Charge packets are spread amongst multiple pixels by diffusion
- Consequences for spectroscopy:
 - Multi-pixel events get extra read noise
 - Some charge is lost even from 'single-pixel' events
 - Leads to noise-dependent broadening & 'tail'



Small-but-Tall Pixel Effects

The effects of charge diffusion on soft X-ray response for future high-resolution imagers

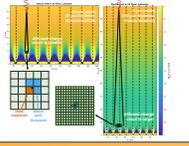


Eric Miller, Richard Foster, Gregory Prigozhin, Marshall Bautz, Catherine Grant, Beverly LaMarr, Andrew Malonis (MIT Kavli Institute), Craig Lage (UC Davis)



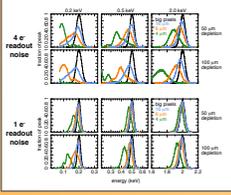
Motivation

Future solid state imagers for high-spatial-resolution X-ray missions such as AXIS and Lynx will require an unprecedented design of "tall and skinny" pixels: small pixels to sample the sharp PSF, and deep depletion for hard X-ray sensitivity. This presents challenges for the detection of soft X-rays, since the charge cloud produced by a photon near the entrance window diffuses to multiple pixels by the time it is collected at the rear surface, complicating energy reconstruction. We present simulations of this process to inform the design of such future detectors.



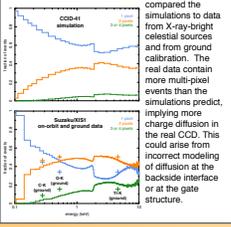
Response vs. Pixel Size

Below we show the response to monochromatic photons due to charge diffusion for various pixel sizes and high (top) and low (bottom) readout noise. Wider and shorter pixels provide better knowledge of the photon energy, especially at softer energy and with higher readout noise, where charge is lost below the threshold in neighbor "spilt" pixels.



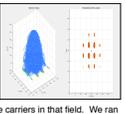
Comparison to Real Data

To validate the simulations, we simulated charge diffusion in a real X-ray detector for which we have substantial data, the MIT/Lincoln Laboratory CCID-41 BI device flown on Suzaku (Koyama+2007). We compared the simulations to data from X-ray-bright celestial sources and from ground calibration. The real data contain more multi-pixel events than the simulations predict, implying more charge diffusion in the real CCD. This could arise from incorrect modeling of diffusion at the backside interface or at the gate structure.



Charge Diffusion Simulations

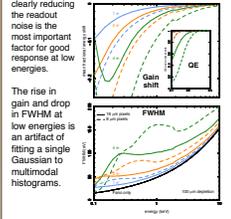
We simulated the diffusion of charge clouds with Poisson, CCD (Lage+2017), a semiconductor simulator that models the electric field in the detector and solves Poisson's equation for the motion of charge carriers in that field. We ran this for a variety of notional back-illuminated (BI) CCDs with depletion depth of 50-100 μm . The cloud diffusion is well-modeled by a two-dimensional Gaussian for interactions throughout the device. For each notional detector and for a grid of photon energies, we simulated 50,000 photons attenuated by the Si and the resultant charge diffusion. Each charge cloud was randomly projected onto a grid of pixels as if it were read out, using different pixel sizes and adding Fano noise and various amounts of readout noise. The resultant "events" were processed similarly to X-ray data.



Response vs. Readout Noise

Below we show the mean energy shift, QE, and response FWHM as a function of energy for two likely pixel sizes and various readout noise. Larger pixels yield substantial improvement in all metrics, but clearly reducing the readout noise is the most important factor for good response at low energies.

The rise in gain and drop in FWHM at low energies is an artifact of fitting a single Gaussian to multimodal histograms.



Summary

The simulations show that while larger pixels and thinner depletion improve the soft X-ray performance, reducing the readout noise has a dominant effect in all cases. Since compelling science requirements often compete technically with each other (high resolution, soft X-ray response, hard X-ray response), these results can be used to find the proper balance for a future high-resolution X-ray instrument.

Future Work

We will validate the simulations using ground data from newer CCID-80 devices, and explore sub-pixel positioning for various pixel sizes.

References

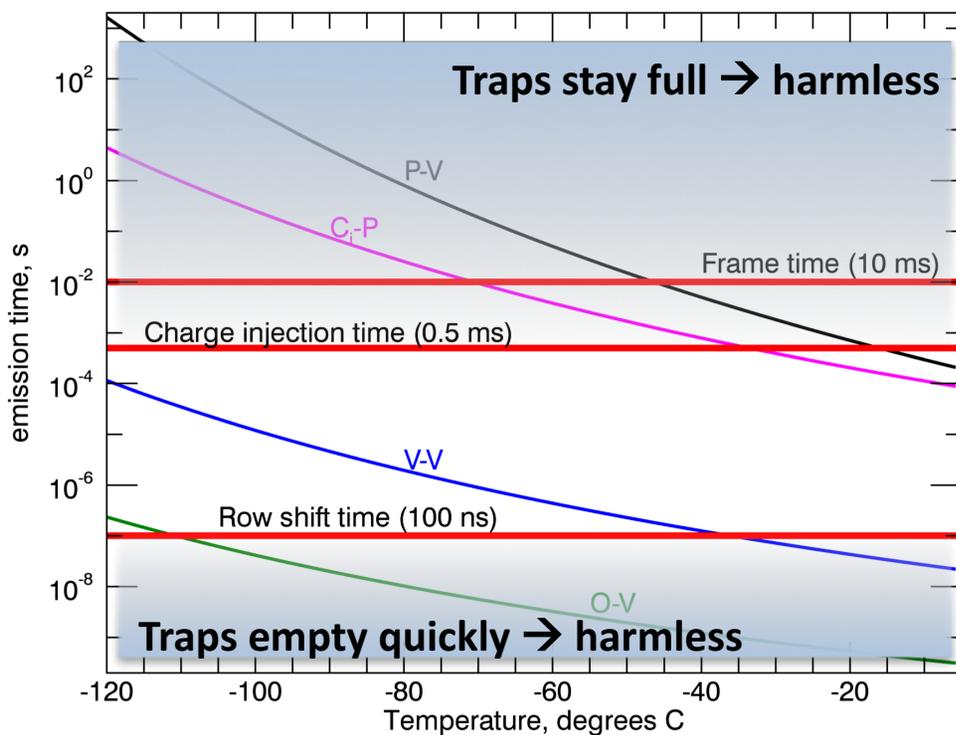
Bautz+2016, SPIE, 10669-43
Lage+2017, JHEP, 13, C03991
Koyama+2007, PASJ, 59, 23
Lage+2017, JHEP, 13, C03991
Mushotzky+2018, SPIE, 10699-80

We gratefully acknowledge support from NASA APRA grant NNA14EE00 and NASA Strategic Astrophysics Technology grant 80WJSC18W0126

- Lynx HDXI requires small ($16 \times 16 \mu\text{m}$) but tall ($\sim 100 \mu\text{m}$) pixels too.
- This will affect both soft X-ray QE as well as spectral resolution.
- May drive noise requirements below present estimates.

See Eric Miller+ Poster 10699-205 THURSDAY!

Radiation Tolerance



G. Prigozhin

- Fast HDXI transfer rates affect CCD radiation tolerance. Only traps with:
 $0.1 \mu\text{s} < t_{\text{trap}} < 0.5 \text{ ms}$
matter for HDXI
- Demonstrated hardening techniques (charge injection, buried channel trough) → satisfactory radiation tolerance for Lynx
- For worst case detector format:
Gain spread of order 10^{-3} yr^{-1}
FWHM change of order 10^{-2} yr^{-1}
- We will test these projections!



Next Steps

- Characterize low-speed, high-responsivity SiSeRO amplifier
- Complete fabrication of 2nd generation DCCD test device (shown)
- Features:
 - Back-illumination
 - Frame-transfer architecture
 - pJFET and fast SiSeRO amplifiers
 - Radiation hardening ('trough' and charge injection)
- Characterize low-energy response and radiation tolerance



Summary

- MIT Lincoln DCCDs at 2.5 MHz, with CMOS-compatible clocks, show:
 - FWHM $\lesssim 150$ eV at 5.9 keV
 - Noise $\lesssim 6$ electrons RMS, responsivity 21 $\mu\text{V}/\text{electron}$
 - Serial CTI $< 0.8 \times 10^{-6}$
- Our NASA-funded SAT program is producing next-gen DCCDs to:
 - Demonstrate noise performance required by HDXI ($< 4 e^-$ RMS)
 - Demonstrate soft X-ray ($E \sim 0.3$ keV) performance required by HDXI
 - Evaluate radiation tolerance and optimize operating temperature
- DCCDs are an attractive detector technology for Lynx